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IMPLEMENTATION OF FIRE MODELS IN OPENSEES

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Abstract. *In the modern routine design of structures, computational modelling of the structural behaviour under natural and man-made hazards has become more and more important. The capabilities of analysing the structural performance under such hazards (e.g. snow, wind, earthquake, impact) have been widely utilized into the mainstream of nonlinear finite element method (NFEM) based software, such as SAP, ANSYS, ABAQUS etc. However, there are very limited software options to characterize fire impact on structures. In general, there are two types of computer programs for simulating structural behaviours in fire: research-oriented and business-oriented. The former such as SAFIR, VULCAN, and ADAPTIC address specific modelling problems, because of a limited number of users and a small team of developers. The latter such as ABAQUS, ANSYS and LS-DYNA are used commercially by researchers and industry across the world. Nevertheless, limited access to source codes, lack of transparency of the computational framework, high cost of purchase and maintenance are major limitations.*

In 2009, OpenSees was adopted at the University of Edinburgh for further development to enable it to perform structural fire analysis. Facilitated by its open-source nature, a large number of thermal capabilities have been added to the framework by Usmani et al. [1]. Significant contributions in terms of heat transfer and fire modules have been made to the framework in developing the ‘Thermal’ version of OpenSees [2]. After verifying and validating the thermo-mechanical analysis of OpenSees [3], [4], users are able to model structures under extreme thermal actions (such as those resulting from fire conditions) through defining arbitrary non-uniform temperature distributions across and along an element. This paper reviews the existing fire modules in OpenSees, including uniform compartment fire models and localised fire models. The latest development of advanced fire modules, i.e. smoke zone models and travelling fire models are introduced. Finally, a case study using the FIRM zone model in OpenSees is investigated, for validating its results against the original FIRM-QB software package [5], and further exploring the thermal impact from different fire scenarios using OpenSees.

1 A REVIEW OF EXISTING FIRE MODELS IN OPENSEES

Conventional structural fire design codes are based on isolated single structural members with simply-supported boundary conditions under standard fire test exposures, which refers to a heating curve such as ISO-834 standard fire, or ASTM-E119 fire. The standard fire curve along with external fire curve, and hydrocarbon fire curve are categorized as nominal fire curves in Eurocode [6]. This type of fire curve is basically a time-temperature relationship, which stands for the case of a fully developed fire in a compartment (see Fig. 1(a)). All the above-mentioned fire curves are added in the OpenSees fire module as *NominalFireEC1* class [2]. Different from the nominal fire curves, the parametric fire curves [6] which consider fire growth rate, fire load density, and characteristics of the compartment (e.g. thermal boundaries, openings, geometric quantities, etc.) are also added in OpenSees as *ParametricFireEC1* class [2].

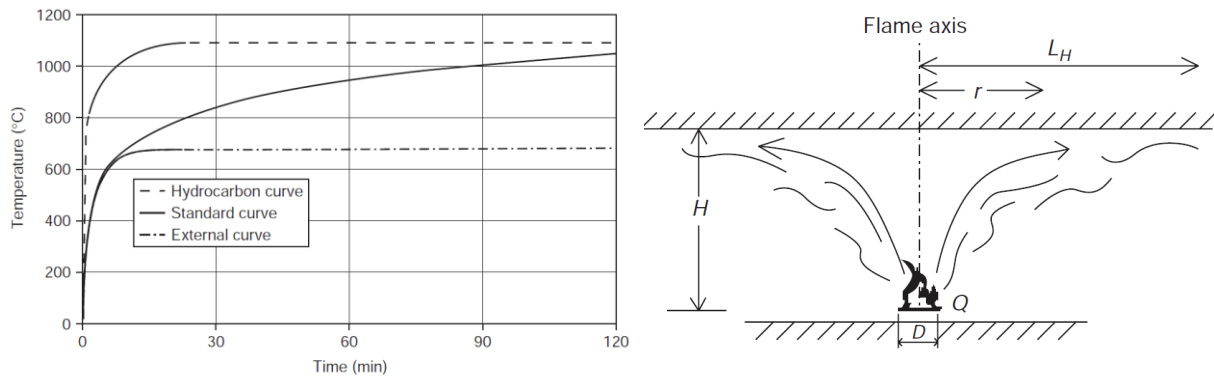


Figure 1(a): Three different nominal fire curves in Eurocode; Figure 1(b): Localised fire model in Eurocode. [7]

Although these fire models are relatively simple, they are still widely used for both research and design purposes in fire safety engineering. A user defined fire curve (*UserDefinedFire* class) [2] is also included in the OpenSees fire module for providing more flexibility. These idealised uniform fire models are all assumed to have the same temperature distribution in the entire compartment at a specific time.

Further, in the case of isolated fuels burning in a large space (e.g. vehicles burning in a car park), localised fire models are regarded to be appropriate for simulating such burning scenarios. The Hasemi localised fire model (adopted in the Eurocode [6], see Fig. 1(b)), Alpert ceiling jet model [8], SFPE handbook-based localised fire model [9], and a user defined idealised local fire model, are added in OpenSees fire module as *LocalizedFireEC1* class, *AlpertCeilingJet-Model* class, *LocalizedFireSFPE* class, *Idealised Local Fire* class respectively [2], [10]. These localised fire models, in their mathematical nature, are all correlational equations between incidental heat fluxes on the structural surfaces and radial distance from the fire source.

2 ZONE MODELS AND TRAVELLING FIRE MODELS IN OPENSEES

In a prescriptive structural fire design code, the fire exposure is usually constrained by the code with limited room for discussion (e.g. nominal fire curves in Eurocode). In a performance-based structural fire design code, the practitioners have greater flexibility and the fire is usually related to realistic fire loadings (e.g. localised fire models, zone models, and travelling fire models, etc.). The newly added two zone model classes, *ZoneModel_ASET*, *ZoneModel_FIRM*, enable the fire module in OpenSees to simulate the transient generation of a hot smoke layer upon the compartment ceiling. The transient height and temperature of the smoke layer are calculated according to a set of ordinary differential equations (ODEs) based on the mass and energy conservations (see Fig. 2(a)) [5].

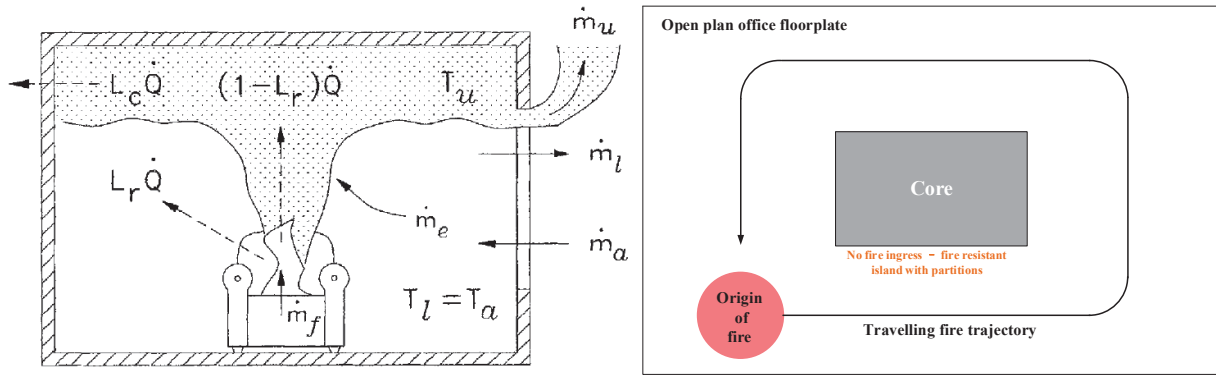


Figure 2(a): Fire problem modelled using FIRM zone model [5]; Figure 2(b): Plan view – extended travelling fire method framework.

The difference between *ZoneModel_ASET* and *ZoneModel_FIRM* is that, *ZoneModel_FIRM* can handle the compartment with vertical natural ventilations, however *ZoneModel_ASET* is basically filling the smoke in a ‘box’ without considering any significant openings.

More recently, a very active research frontier on performance-based structural fire design named ‘travelling fires’, is evolving [11]. This type of fire scenario is developed for characterising large compartment fires, which may burn locally and tend to move across entire floor plates over a period of time. An extended travelling fire method (ETFM) framework was developed by Dai et al. [12], and further implemented into OpenSees fire module [13]. This ETFM framework is based on a mobile version of Hasemi’s localized fire model combined with a simple smoke layer calculation – the FIRM zone model. The *ETFM_TravellingFire* class is added to the OpenSees fire module to calculate the spatially and temporally non-uniform heat fluxes for different structural elements, produced from the ‘summation’ of the heat fluxes from the FIRM zone model and Hasemi localised fire model. *TravellingFireFuel* class is included to account for the uniformly distributed meshed fuel cells, and *TravellingFireFuel_Iter* class is introduced for looping over all the meshed fuel cells (i.e. *TravellingFireFuel*) to check if the fuel is currently on fire, or not, at each time step, then aggregating them as the entire burning fuel area.

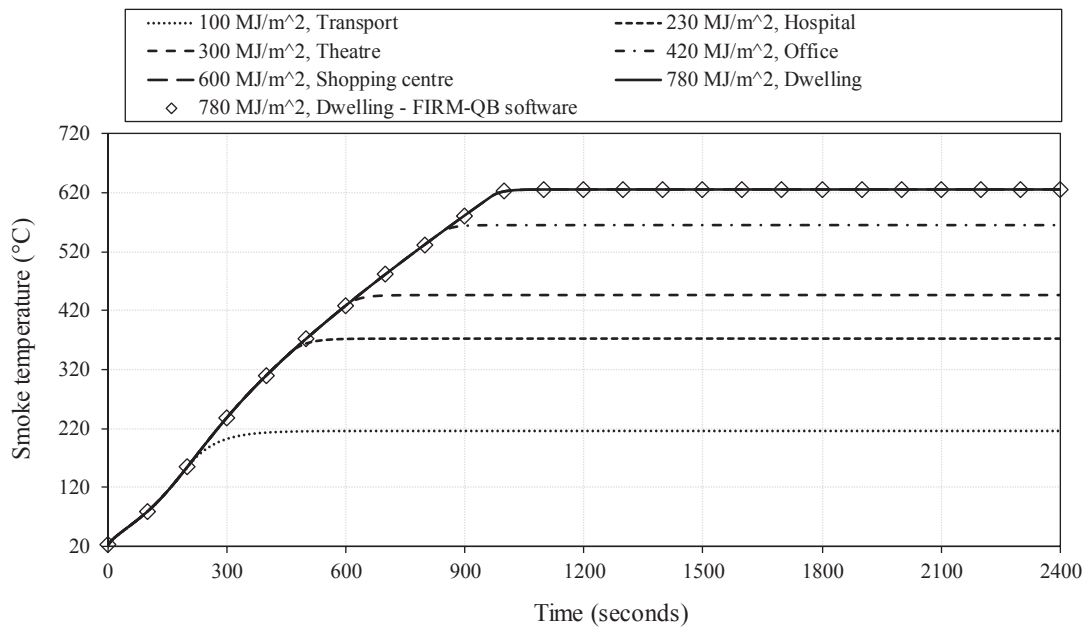


Figure 3: Smoke temperature evolution with various fuel load densities

3 A CASE STUDY USING FIRM ZONE MODEL IN OPENSEES

To validate the results produced from the OpenSees FIRM zone model against the original FIRM-QB software package due to Janssens [5], and to further explore the thermal impact from different fire scenarios, a case study is performed. The investigated compartment floor area is 468m^2 , with the clear floor height 3.85m. The total vent widths of this large compartment are 28m. The soffit height and sill height are 3m and 1m respectively. A ‘base line scenario’ of the fires is assumed with fuel load density ($q_{f,k}$) 570 MJ/m^2 , heat release rate per unit area (RHR_f) 500 KW/m^2 , and fire spread rate (v) 10 mm/s . Different fire scenarios are generated with changing $q_{f,k}$, ($100\text{--}780\text{ MJ/m}^2$) but keeping the other two values as constants. Figure 3 shows that the results generated from OpenSees agree well with FIRM-QB software, and illustrates the smoke temperature evolution with various fuel load densities according to Eurocode 1 [6].

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